CHAPTER EIGHTEEN

MONITORING WEATHER HAZARDS ON RURAL ROADS USING REMOTE SENSING AND GIS*

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Introduction

Approximately 60 percent of the population and 99 percent of the land in New Mexico is rural (NADO, 2003). Rural roads constitute 95 percent of all roads in New Mexico, and of the 61,422 miles of Federal Highway Administration (FHWA) reported roads, over 38,000 miles or 62 percent are unpaved. Unpaved roads provide critical lifelines for a substantial proportion of the state's population. The non-urban poor are disproportionately affected by disruptions to the rural road network and are some of the most inadequately served by emergency services, which impacts thousands of individuals in New Mexico, a state that ranks 3rd in the nation in percent of rural poor. Road maintenance and repair are vital to these populations often representing Native American and other minority groups, where disruptions can cause serious problems resulting in loss of life, livestock, and livelihood. Severe weather and flash flooding pose significant problems of accessibility for residents and emergency services personnel, and cost millions of dollars in road maintenance and lost commerce annually. The ability of state and local governments to meet the challenges posed by the thousands of miles of unpaved roads is limited by inadequate and untimely reporting of road conditions. The Weather-Related Road Hazards Assessment and Monitoring System (WRRHAMS) addresses these challenges.

The goals for the project are to develop a system that facilitates the use of hydrologic models and automated precipitation data acquisition and

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processing systems by transportation professionals. The system is designed such that no knowledge of geographic information systems (GIS), hydrologic modeling or the specifics of processing near-real-time precipitation data are required of the end user. The application uses a standards-based web platform that allows remote access to the most current data and modeling environment with an Internet connection and web-browser. This approach provides a transportation decision-support system through a sophisticated but easy to use geospatial analysis and visualization environment requiring only minimal computer system resources.

The development of WRRHAMS was accomplished in three phases: 1) automated data acquisition; 2) hydrological model development; and 3) client interface production. Automated data acquisition involved programming perl scripts to acquire, process, and make available near-real-time precipitation data. Hydrological model development required implementation of processing algorithms to integrate the dynamic precipitation data with hydrologic modeling tools that utilize distributed rainfall data and other input parameters. A web-based client interface was developed that presents the user with the most recent hydrologic model results, precipitation data, transportation network data, and other background layers. This interface facilitates visual identification of road network segments that intersect regions of potentially high runoff or direct precipitation.

Study Area

A prototype implementation of WRRHAMS was undertaken in McKinley County, New Mexico to test the effectiveness and utility of using near real-time weather and environmental data with runoff modeling to identify remote road locations likely to have suffered damage from precipitation events or locations that are candidates for grading following local precipitation. McKinley County, located in northwestern New Mexico (Figure 18-1), is a predominantly rural county with over 54,000 residents who depend on a network of unpaved roads for access, commerce, and emergency services. As such, it is ideally suited as a test bed for WRRHAMS. The 9,926 miles of unpaved roads represent over 94 percent of all roads in the county and have proven to be a significant challenge to the county’s transportation division. They have been actively seeking tools to maximize their expenditure of limited resources. The McKinley County GIS Department provided the necessary road network data, and is currently working with the University of New Mexico’s Earth

Data Analysis Center (EDAC) to evaluate WRRHAMS as a means of improving the efficiency and cost effectiveness of rural road maintenance operations in the county.

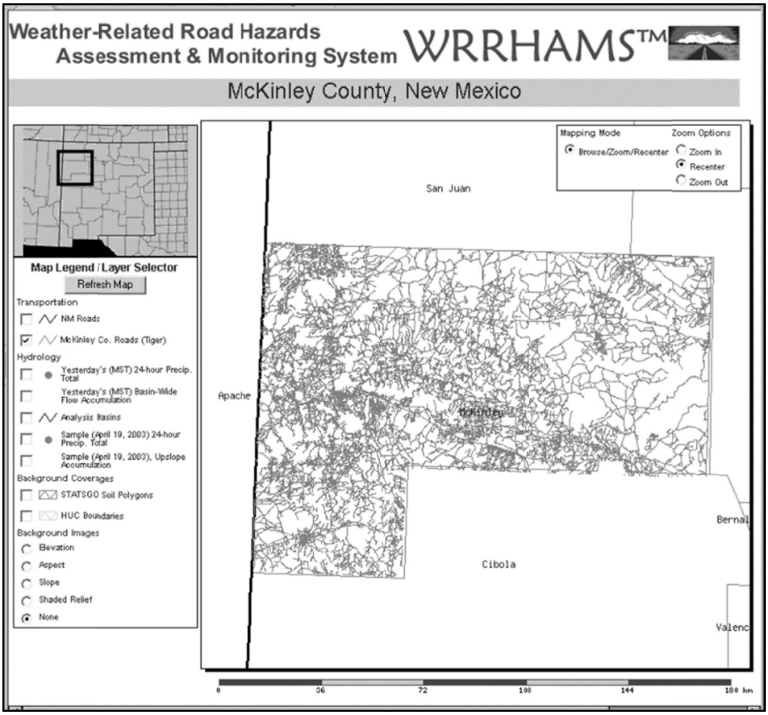

Figure 18-1. McKinley County, New Mexico showing WRRHAMS interface and road network

Data

Data employed in the application include background environmental data, transportation network information, administrative boundary data, and near-real-time precipitation data. These data consist of both source-data like soil characteristics, digital-elevation data, and precipitation data; derived data such as slope, aspect, analysis basins, and flow-accumulation; and model results such as weighted flow-accumulation. Detailed information about the broad categories of data employed in the application, the sources for those data, and the processing steps used in data development is presented in the following sections.

Base Data

Environmental data provide the foundation for the hydrologic modeling and data visualization components of the application. Source data utilized in the application include:

1. Soil data derived from the State Soil Geographic Database (U.S. Dept. of Agriculture, 1991, 2003) including parameter values of hydrologic interest. These values are: a) available water holding capacity, b) layer depth, c) soil erodibility factor, d) permeability rate, and e) depth to bedrock.
2. Drainage basin data derived from the GIS coverage representing the "Hydrologic Units of the Conterminous United States" (Steeves and Nebert, 1994). This layer is used for visualizing the boundaries of the hydrologic units defined for the National Water-Quality Assessment Program (NAWQA).
3. 30 m Digital Elevation Data (U.S. Geological Survey, 2003)

Environmental data layers derived from the digital elevation model include:

1. Aspect (in degrees, classified into 8 cardinal directions for mapping purposes).
2. Slope (in degrees, divided into 4 classes for mapping purposes).
3. Shaded relief (a grayscale representation of the elevation data).

Following Reed and Maidment (1995), all environmental datasets are converted to an Albers Equal Area projection for integration with standard hydrologic modeling procedures. These procedures depend on equal area units throughout an analysis region for the maintenance of precipitation depth – volume relationships (Reed and Maidment, 1995). These datasets (with the exception of the shaded relief which is used solely for visualization purposes) provide data necessary for implementing a wide range of hydrologic models.

Two transportation data sources are employed in the prototype application developed for McKinley County. These data are the New Mexico "Major Roads" line coverage published by ESRI (2003) as part of the ArcGIS 8.2 distribution, and the U.S. Census Bureau TIGER/Line Files (2001) representing road centerlines for McKinley County.

Precipitation Data

The use of near-real-time precipitation data is key to providing up-to-date information about potential localized impacts of precipitation events on rural road networks. In an effort to minimize labor requirements, while also providing predictable availability of data, an automated system for acquiring, processing, and displaying precipitation data was developed. The resultant data used in this application are described below.

The National Centers for Environmental Prediction (NCEP) of the National Weather Service create mosaicked hourly, 6-hourly, and 24-hourly precipitation data files (collectively referred to as the 'National Stage IV QPE Product [NCEP, 2003a]). These data are developed from the regional hourly and 6-hourly multi-sensor precipitation estimator (MPE) that integrates NEXRAD RADAR data with rain gauge data. These data files cover the continental United States and are available for download from the NCEP, as uncompressed hourly and 6-hourly files for the past seven days (NCEP, 2003b), and as daily TAR archives for the previous 6 months (NCEP, 2003c). New national mosaics for the hourly and 6-hourly products are generated by NCEP when new automated production or manual quality controlled Stage III precipitation data are received from the regional River Forecast Centers (RFC). Lag-time between the data collection by the RFCs, and distribution to the data download area of NCEP typically takes from 1-12 hours (NCEP, 2003c).

The precipitation data in the Stage IV products are distributed over a nominal 4-km grid. The actual spacing between grid points depends on the location within the Numerical Weather Prediction (NWP) Hydrologic Rainfall Analysis Project (HRAP) based grid. The total grid consists of 1121 rows and 881 columns in a polar stereographic projection that at its maximum extent ranges from roughly 23.1N-53.5N Latitude and 60.0W-134.0W Longitude. The precipitation values for each grid cell are in mm precipitation over the period of the data set (i.e. hourly or six-hourly). Preparation of the hourly precipitation data for integration with the other data and the hydrologic modeling system requires several steps. All integration processing is automated allowing unattended data retrieval and processing. Re-projection of the HRAP grid locations is accomplished through the use of custom perl script code that converts grid points to latitude and longitude, using the Fortran subroutine *w3fb07.f* made available for download by the NCEP (2003d). After conversion to latitude and longitude, the grid locations are projected into the same Albers equal area projection used for the background datasets. This process results in a text file containing the coordinates of each grid location in Albers equal area meters, with the order of the coordinate pairs matching the order of values that are obtained when the binary, GRIB formatted, precipitation data are extracted to a text file (using the *wgrib* utility [NCEP, 2003e]). To maximize flexibility in processing and analysis of the precipitation data, the individual measurement values and their associated grid coordinates are imported into PostgreSQL (an open source object-relational database) for summarization and processing.

For each location in the grid, precipitation data for the previous day's 24-hour accumulated precipitation are generated and saved as an ArcView shapefile. To provide for basic quality control, additional information about the number of hourly precipitation values contributing to the total for each grid point is also captured. This process allows the identification of grid points for which the precipitation total represents fewer than 24-hourly precipitation values. In the case of the McKinley County application, the resulting shapefile contains 4850 individual precipitation values for the area within and surrounding the county (Figure 18-2).

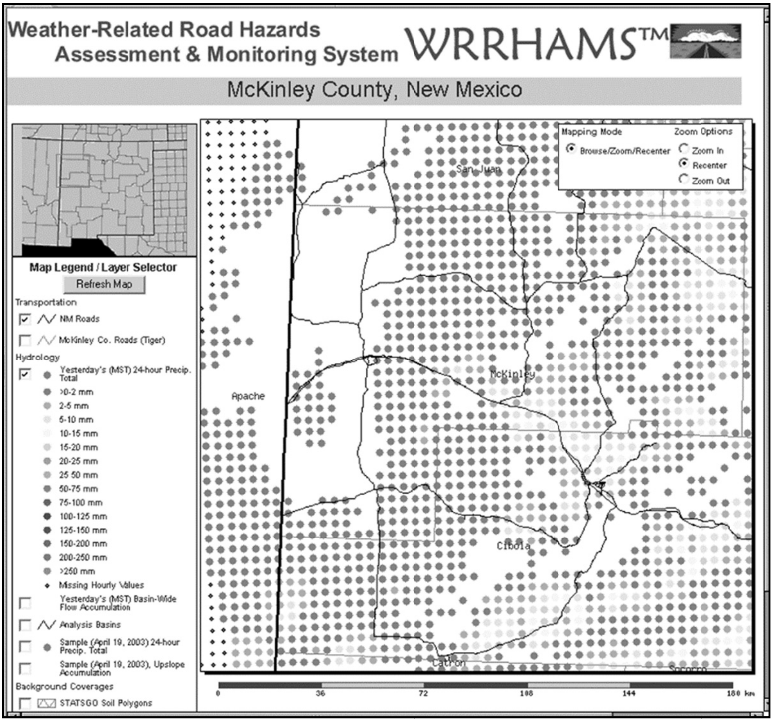

Figure 18-2. WRRHAMS client interface: 24-hour precipitation total data

Methods

The McKinley County WRRHAMS prototype application required the use of a hydrologic model in an analysis and visualization environment. This is accomplished using existing watershed models in the GRASS GIS environment. In addition to the analysis and visualization functionality, WRRHAMS requires that the analytical results be delivered via the web to remote clients.

Hydrologic Modeling

The hydrologic modeling component of the project is ongoing. To model runoff, a basic weighted flow accumulation model employing a combination of the 24-hour precipitation data and sub-basin flow accumulation (a static value generated using watershed analysis algorithms implemented in the GRASS GIS [GRASS Development Team, 2003]) is used. The hydrologic modeling process is currently run at a 250m cell resolution within individual basins. This yields a relatively coarse-resolution raster data set that allows for the visualization of potential flow accumulation within each basin.

The steps involved in the hydrologic modeling process are:

1) Delineation of basin boundaries (a one-time process).
2) Calculation of flow-accumulation within each basin (i.e. the number of upslope cells for each cell in the flow-accumulation raster – a one-time calculation). The current model assumes each basin is a closed unit without inflows or outflows.
3) Calculation of the average precipitation over each basin (executed each time a new 24-hour flow accumulation estimate is needed).
4) Calculation of the weighted flow-accumulation for each basin by multiplying the static flow-accumulation raster obtained in step 2 by the average precipitation for each basin obtained in step 3.

This process yields a raster that displays a relative flow-accumulation for all of the analysis basins defined for the region (Figure 18-3).

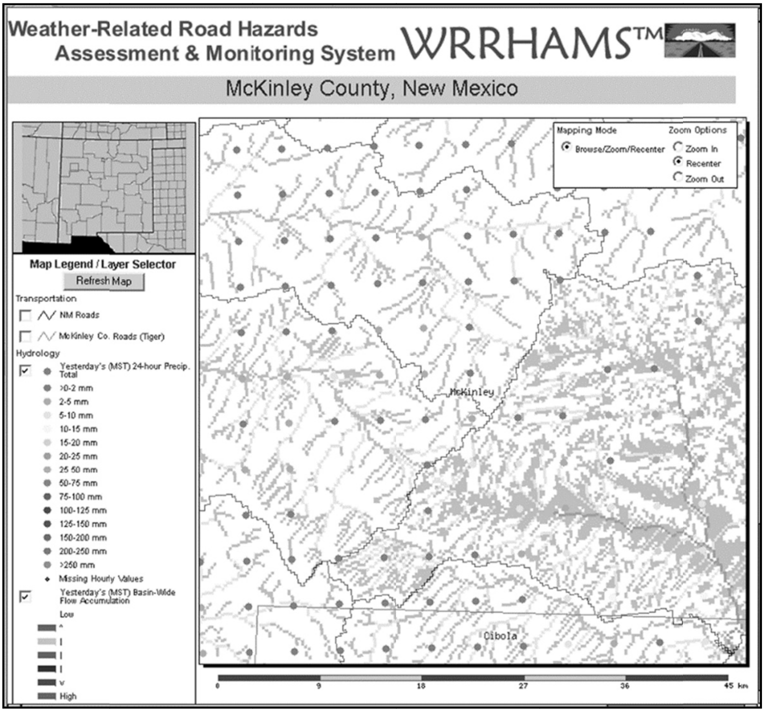

Figure 18-3. WRRHAMS client interface with a close-up view of the flow accumulation raster and analysis basins

Application Delivery and Analysis

The final component of the application presents the results of the hydrologic model to the user in a form that provides a simple interface integrating the model results with transportation network information (Figure 18-4). The resultant user interface is provided through a custom web-based mapping environment that allows the user to toggle the display of any data layers while also providing basic exploration tools for zooming and panning. These abilities are illustrated in Figures 18-1 through 18-4, where each figure displays a different combination of active layers and map extents, all within the actual web-interface. The mapping environment is constructed using MapServer, an open source internet mapping application developed at the University of Minnesota (Regents of the University of Minnesota, 2003).

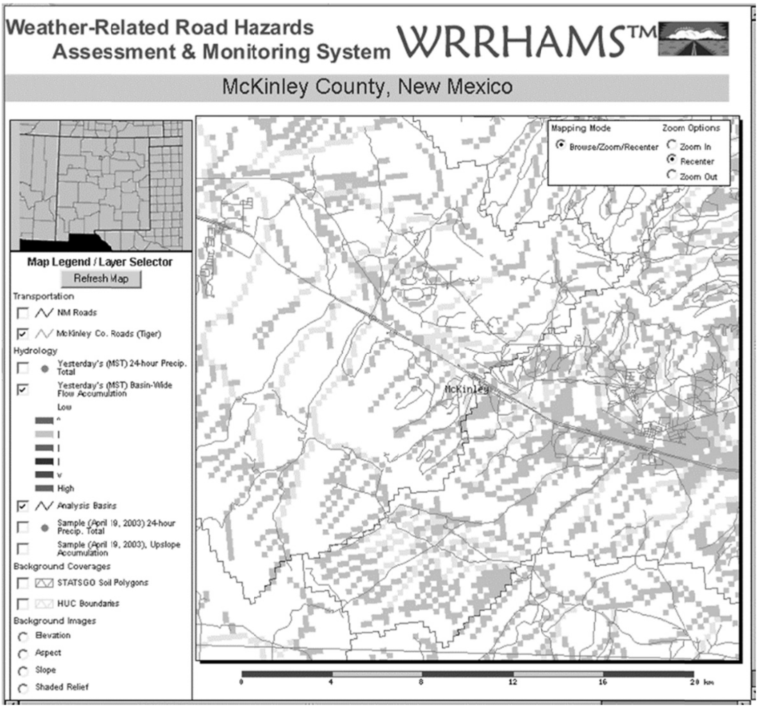

Figure 18-4. WRRHAMS client interface with a close-up view of the flow accumulation raster and TIGER road network

Application Development and Assessment

The WRRHAMS application has been developed using a combination of open source tools. Data processing is performed using wgrib (NCEP, 2003e), proj (Warmerdam, 2003), and GRASS GIS (Grass Development Team, 2003). PostgreSQL is used to store the data (PostgreSQL Global Development Group, 2003). The GIS used for data visualization is GRASS. The web application was developed using MapServer (Regents of the University of Minnesota, 2003). Application automation has been accomplished through the use of perl scripts (Perl Mongers, 2003) that: 1) download and import the previous day's precipitation data into the PostgreSQL database; 2) obtain summary precipitation data from the PostgreSQL database and write those data into a point shapefile for use both in the web-mapping environment and the hydrologic model; and 3) run the hydrologic model in GRASS GIS, producing additional raster data that are presented to the user through the web interface. The application is hosted on a server running RedHat Linux 8.0.

An initial assessment of WRRHAMS was conducted using simulated rainfall accumulations to evaluate the utility of the approach in identifying road/stream intersections potentially at risk for damage from excessive runoff. Runoff resulting from the simulated rainfall data allowed the identification and ranking of at risk road segments that would have been impacted by the simulated rainfall event. Of the fifteen road/stream crossings experiencing runoff from the event, the model identified two having runoff values in excess of 3000 cfm and which are potentially susceptible to erosion (Figure 18-5).

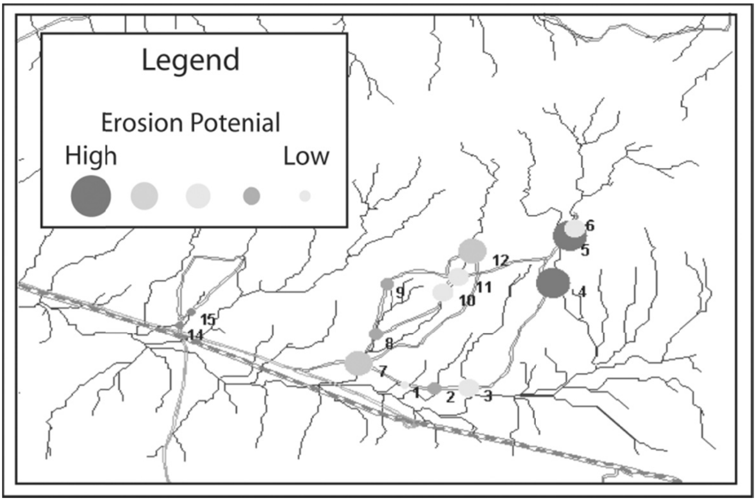

Figure 18-5. Road/stream intersections ranked by probability of erosion

Conclusions and Future Development

The current application is both an operational transportation decision support system for visualizing transportation network information in a near-real-time hydrologic framework and a demonstration of capabilities. As a demonstration project, enhancement of WRRHAMS will take place in several areas. Areas currently under consideration are: 1) implementation of a more detailed and systematic hydrologic model integrating vegetation, soil, and soil-moisture data; 2) use of more application-specific transportation network data such as road surface type and maintenance status; 3) automated identification of road segments that intersect areas of high flow; 4) display capabilities and query tools for specific features (i.e. road segments, drainage locations, etc.); and 5) addition of end user annotation and data updating capability.

The McKinley County New Mexico implementation of the Weather Related Road Hazards Assessment and Management System has already been shown to be a valuable tool for maintenance of rural roads. Feedback from McKinley County users indicates that the web-based framework for a transportation decision support system is a cost effective means to improve rural road maintenance and repair. In addition, the McKinley County staff has also suggested improvements and alternative applications for the WRRHAMS environment.

Acknowledgements

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